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Implementing Green Chemistry Principles In Laboratory Practices

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Abstract

It is crucial to integrate green chemistry as well as security into laboratory culture using a systems thinking approach, given that chemists will be responsible for developing molecular-level innovations that address global challenges. It is critical for both society and the environment to have chemists trained with the knowledge and values necessary to perform this task in the safest manner possible, as this affects not only the chemical industry but also society as a whole in the pursuit of a sustainable future. Green chemistry is currently recognized as the framework for conducting chemistry in a way that is beneficial to life. This article highlights the potential of conceptualizing green chemistry from the perspective of systems thinking to foster a laboratory environment that prioritizes safety. This can result in a shift in the emphasis of the security culture from compliance to proactivity, since chemists gain ownership and control over their safety by evaluating the risk associated with conducting a reaction. One approach that is emphasized is the Guide to Green Chemistry Experiments for Undergraduate Organic Laboratories. The guide employs DOZN 2.0, a green chemistry metric that enables a quantitative approach to identifying and evaluating the dangers associated with a chemical reaction. Green chemistry is an integral component of the Green Laboratories movement and assists research institutions in achieving their safety and sustainability objectives. However, effective communication and collaboration between environmental safety and health (EH&S) and environmental sustainability professionals are crucial for the successful implementation of these initiatives. Gaining insight into the impact of motivational focus on attitudes and perceptions can facilitate more effective collaboration among stakeholders and enable Green Laboratories to implement these techniques more efficiently.

Keywords: interdisciplinary/multidisciplinary, instruction, organic chemistry, laboratory, green chemistry, safety, hazards, upper-division, undergraduate graduate, education.

1. Introduction

As the fundamental science responsible for constructing molecules, chemistry influences every product that we use and consume. Regrettably, chemistry has been frequently tarnished by the unintended repercussions of certain chemical processes and products. (1) In contemplating the future, it will be imperative to guarantee that the field of chemistry operates in a manner that is conducive to life and does not cause any damage. (2) Many organizations are attempting to achieve this by integrating the United Nations Sustainable Development Goals (UN SDGs), a collection of seventeen objectives aimed at "eradicating poverty, safeguarding the environment, and enhancing the well-being and opportunities of all individuals globally," into their business sustainability strategies. (3) Since the solutions to our global challenges will be developed at the molecular level, chemists must (4) possess the knowledge, abilities, and culture to support these objectives in the safest manner feasible. To solve problems with human health and the environment in mind on purpose and to investigate their chemistry through the lens of safety and sustainability, chemists must learn and implement green chemistry.

The concept of green chemistry entails the development of chemical products and processes that minimize, abolish, or substantially reduce the consumption or production of harmful substances. (5) Green chemistry actively and consistently considers the hazard of a chemical reaction at the molecular level, beginning with the hazard of the initial materials and continuing through the reaction conditions and final product. Developed by Dr. Paul Anastas and Dr. John Warner (5) and adopted by the American Chemical Society (ACS) (6) (Figure 1), green chemistry employs a framework of 12 Principles to assist chemists in considering how to minimize the danger of chemical reactions to human health and the environment.

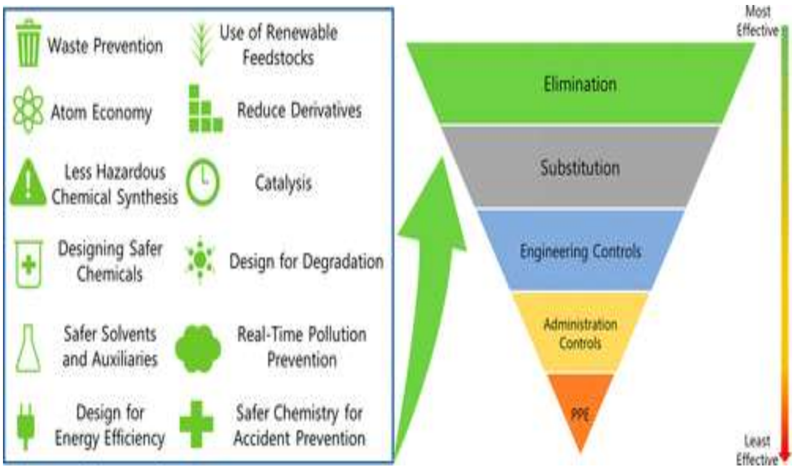

Figure 1. Implementing the Twelve Principles of Green Chemistry.

While several principles do touch upon safety considerations, Principle 12, "Safer chemistry for accident prevention," most explicitly establishes the correlation. The correlation between laboratory safety culture and green chemistry methodologies is evident in this instance, as the selection of substances and their forms for chemical processes ought to reduce the likelihood of chemical accidents—such as flames, explosives, and releases. It is important to mention that the fulfillment of Principle 12 necessitates the application of additional green chemistry principles. Due to this intersection of safety and green chemistry, the Committee on Chemical Safety of the American Chemical Society recommends that all first- through fourth-year undergraduate chemistry students be exposed to the subject. (7,8)

An emerging paradigm in safety education entails fostering laboratory personnel an awareness of hazard evaluation and risk reduction. The aforementioned approach is streamlined into RAMP (Recognize hazards, Assess risks of hazards, Minimize risks of hazards, Prepare for emergencies). In addition to being structured and adaptable, this methodology is scalable, collaborative, and transferable. RAMP is advantageous as an instructional strategy for chemical safety due to its numerous convergences with the principles of green chemistry. (10−12) Similar to the complementary nature of RAMP and green chemistry, the application of green chemistry instruments, including DOZN 2.0 (13), which is elaborated upon in this article, assists scientists in identifying (R) and quantifying (A) the hazards and risks associated with chemical reactions.

Minimizing (M) risks is possible within the framework of green chemistry through the elimination or substitution of hazardous substances; numerous resources are at one's disposal to offer viable alternatives. (14) It is evident that the most efficient method of mitigating risk is to eliminate a hazard or replace it with a less hazardous or nonhazardous alternative (17), as depicted in the Hierarchy of Controls Pyramid of the National Institute for Occupational Safety and Health (NIOSH) (Figure 1, right). Once again, safety and ecological chemistry intersect. For instance, through the application of green chemistry Principle 3, which pertains to the synthesis of less hazardous chemicals, chemists will be able to devise synthetic processes that produce and utilize substances that are environmentally and human health safe. By employing the principles of green chemistry—namely elimination, substitution, and reducing the reliance on engineering controls—too much safety is compromised (Figure 1).

As a result, instruction in the theory and implementation of green chemistry principles safeguards and enhances the well-being of laboratory personnel.

Nevertheless, complete environmental friendliness is unattainable; that is, no chemical reaction can account for or adhere to all twelve principles. Because all chemicals present a risk at a certain dosage, even in the most advanced green chemistry laboratories, exposure to chemicals must consistently be taken into account. (18) This is because risk is determined by multiplying hazard (the severity of consequences) by exposure (the probability of occurrence). (19)

A substantial improvement in laboratory safety can be achieved through the integration of green chemistry principles and practices into laboratory procedures and culture. In order to accomplish this, collaboration among sustainability administrators, EH&S (environmental health and safety), educators, and researchers is essential for ensuring the well-being of students, faculty, and staff. This partnership is essential for academic institutions to develop a robust safety culture. The ACS Committee on Chemical Safety recommends the following: "Create an intimate working relationship with EH&S personnel across all departmental levels, soliciting their guidance and expertise in safety, and providing EHS with departmental and faculty recommendations grounded in their knowledge of chemistry." (20) While the implementation of green chemistry enables scientists to mitigate personal hazards, systemic safety is not intrinsically linked to any one individual. An institution's safety culture is co-created by its stakeholders and the interdependencies among its system components, including researchers, EH&S experts, sustainability practitioners, and others who interact with laboratories. (21)

At each educational level, a holistic safety culture must be established through the implementation of a systems thinking approach that integrates safety and green chemistry principles into laboratory culture. (22) This is significant because it allows academic institutions to establish a safety culture that can be extended to future career paths. This paper examines approaches to integrating green chemistry principles into research and teaching laboratories with the aim of fostering a robust safety culture. In addition, we analyze critical factors that influence the formation of relationships among various stakeholders.

2. Promoting Green Chemistry and Safety via Greener Laboratories

Research laboratories are considerably more complex than teaching laboratories, which typically have consistent apparatus and protocols that are relatively easy to modify to maximize the incorporation of green chemistry and safety practices. Not only are a greater variety of chemicals and apparatus utilized, but also waste streams are produced; these materials and residues are essential for the research to accomplish its objectives. The integration of Green Chemistry principles into research laboratories is frequently impeded by scientific imperatives. Often, there is a propensity to adhere to a tried and true method that has proven to be effective, rather than attempting something novel that could potentially achieve the same objective.

However, Green Laboratories initiatives have proven to be highly effective in integrating green chemistry and safety principles into the institutional culture of research laboratories. Green Laboratories, an international biopharmaceutical and academic institution movement that has gained significant traction over the last decade, aims to mitigate the ecological consequences of laboratories through the reduction of waste generation, water and energy consumption, and laboratory environment usage. (31) Numerous Green Laboratories initiatives seek to enlighten scientists regarding the ecological consequences inherent in laboratory settings and assist them in discerning secure and sustainable methodologies that can be integrated into their daily routines.

The implementation of Green Laboratories principles results in substantial energy and water conservation, as well as a reduction in the production of solid and chemical waste. While Green Laboratories programs predominantly aim to reduce adverse environmental effects, there is considerable convergence with safety concerns. To illustrate, virtually all Green Laboratories programs will emphasize chemical fume hood best practices that are sustainable. As fume hoods can utilize up to the energy consumption of three and a half dwellings (32) they are an ideal candidate for energy conservation measures in laboratories. Research has shown that by closing the sashes of a fume hood when it is not in use, energy consumption can be reduced by 30–50%. (33)

Maintaining closed sashes is a safety best practice from an EH&S standpoint, as it prevents laboratory personnel from being exposed to physical or chemical hazards that may be present in the hood. Additional safety principles advocated by Green Laboratories encompass the administration and reduction of hazardous waste, proper containment of chemicals, and the mitigation of physical hazards such as ultraviolet radiation, among others. Green chemistry principles are also integral to the best practices of Green Laboratories. A number of Green Laboratories initiatives promote the investigation of safer solvents and alternatives with lower toxicity. In certain circumstances, the programs may direct scientists to publicly accessible resources that facilitate the discovery of chemical substitutes, or they may concentrate on particular waste streams by implementing established alternatives.

Numerous institutions, for instance, require their researchers to implement alternatives to ethidium bromide, a prevalent mutagenic reagent in biology laboratories. (34) Although not presently subject to regulation as a hazardous waste by the Environmental Protection Agency of the United States, certain organizations handle ethidium bromide as hazardous and allocate significant financial resources towards its treatment and disposal. Therefore, adopting alternatives is advantageous in numerous ways. There are numerous alternatives available in the market, and numerous Green Laboratories programs can assist scientists in locating one that meets the requirements of their research.

3. Green Laboratories

Certain Green Laboratories programs additionally inquire whether scientists have investigated alternative methodologies or apparatus that are in direct accordance with the 12 Principles of Green Chemistry.

As an illustration, My Green Lab promotes the investigation of techniques that can be executed at room temperature and pressure, as well as the consideration of solvent-free chemistries, including supercritical CO2 chromatography and solid-state synthesis. Additionally, the DOZN 2.0 instrument can be utilized to assess green chemistry alternatives in a scientific environment. Through the manipulation of experimental parameters and materials, scientists are able to readily discern the advantages of a particular procedure in comparison to another. While it may be challenging for laboratories to implement equipment or practices that adhere to the 12 Principles of Green Chemistry, the act of investigating such alternatives raises scientists' consciousness regarding them and encourages them to contemplate them further.

By means of this process of heightened consciousness and investigation, numerous Green Laboratories programs are capable of effectively transforming the institutional climate of research laboratories to place greater emphasis on environmentally friendly chemistry and safety. At the outset, numerous scientists exhibit apathy towards the principles upheld by Green Laboratories. However, when queried about their adherence to a particular procedure, they frequently reply that it is effective and that is the way they have always operated. However, by documenting the environmental consequences of that process, scientists gain a fresh perspective on their research and a fresh objective to strive for in order to facilitate advancements. Given their central position within the research system and their frequent interactions with relevant stakeholders, scientists can serve as valuable indicators for tracking cultural transformations throughout the entire research system. Through acquiring a more profound comprehension of the sustainability or safety principles that scientists find most inspiring, stakeholders can effectively leverage focused communication strategies, resulting in improved results with reduced exertion.

When collaborating with a laboratory to implement Green Laboratories principles, it can be beneficial to begin with self-implementable behavior modifications for laboratory personnel. For instance, closing the fume vent sash or shutting off the lighting when a room is not in use or at the end of the day. Both of these straightforward tasks necessitate a behavioral adjustment in order to pause, reflect, and recall the execution of the novel activity. As laboratory personnel gain proficiency in implementing these minor modifications, envisioning how they can handle more substantial changes may become less challenging. Additionally, I would suggest beginning by addressing matters that are significant to them. Numerous scientists are eager to minimize their exposure to hazardous compounds and plastic refuse. The preceding example involving ethidium bromide is frequently the starting point for laboratories seeking to reduce hazard exposure. Another is to investigate straightforward replacements, such as heptanes for hexanes or 2-methyl-THF for THF. By assisting scientists in locating resolutions to issues that are significant to them, Green Laboratories programs demonstrate to scientists that positive change is feasible and can have an effect on their work.

As laboratories increasingly embrace Green Laboratories best practices, it is critical that scientists participate in the process of solution identification and implementation. It is preferable to foster an open dialogue regarding the applicability of the 12 Principles of Green Chemistry to a laboratory's operations, as opposed to prescribing particular principles for adoption. By ensuring that the discourse remains pertinent to their particular chemistries and methodologies, researchers can ascertain the most advantageous areas. When scientists are capable of assuming responsibility for a change, it becomes an integral part of the laboratory's culture and the established norm. This final step is the most crucial; when scientists accept responsibility for the change, it becomes ingrained in the lab's culture. While the involvement of safety and sustainability experts is crucial, the laboratory personnel are ultimately responsible for responding to the inquiries of "why do we do it this way" and "how could we do it differently?"

4. Conclusion

Understanding the motivational focus and diverse stakeholder perspectives is therefore essential for establishing a robust safety culture, which is essential for reducing accidents. By implementing green chemistry principles into research laboratory curricula and developing effective stakeholder motivation strategies, it is possible to foster a culture of chemical safety and promote sustainability within the field of chemistry. To ensure stakeholder engagement as laboratory safety education shifts from a compliance-oriented to a hazard analysis and risk minimization-oriented perspective, systems thinking are required. An approach for acquainting scientists with the identification and evaluation of potential dangers in chemical reactions, as outlined in The Guide to Green Chemistry Experiments for Undergraduate Organic Chemistry Laboratories, has been emphasized in this article.

The DOZN 2.0 green chemistry instrument is employed in this guide to facilitate a quantitative approach to the emerging paradigm in chemical safety education. Regarding safety, this instrument and green chemistry are not limited to chemists alone; all researchers should contemplate the possibility of a less hazardous, safer alternative. The significance of this lies in the fact that the application of systems thinking and green chemistry principles to safety education transcends the evaluation of chemical reactions and encompasses sustainability concerns, including waste prevention and the utilization of renewable feedstocks. When examining these concepts, whether independently or as part of a Green Laboratories program, it is critical to consider the overlapping perspectives of various stakeholders so as to maximize the effectiveness of corresponding initiatives. We aim to demonstrate the connection between green chemistry and the broader concept of sustainability with this article, as well as the significance of interdisciplinary communication in fostering a safer and more sustainable society.

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